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(54) Title: IMPROVEMENTS IN AND RELATING TO PHOTONIC CRYSTAL FIBRES		
(57) Abstract <p>A photonic crystal fibre including a plurality of longitudinal holes (220). In which at least some of the holes have a different cross-sectional area in a first region (200) of the fibre, that region having been heat-treated after fabrication of the fibre, from their cross-sectional area in a second region of the fibre (190), wherein the optical properties of the fibre in the heat-treated region (200) are altered by virtue of the change in cross-sectional area of holes (230) in that region (200).</p>		

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Improvements in and relating to photonic crystal fibres

This invention relates to the field of photonic crystal fibres.

5 A photonic crystal fibre is a special form of optical fibre. Single-mode optical fibres are widely used in applications such as telecommunications and sensing. Such fibres are typically made entirely from solid transparent materials such as glass and each fibre typically has the
10 same cross-sectional structure along its length. The transparent material in one part (usually the middle) of the cross-section has a higher refractive index than the rest and forms an optical core within which light is guided by total internal reflection. We refer to such a fibre as a
15 standard fibre.

There are many well-established techniques and machines for handling and processing standard fibres; for example, cleavers use a hard knife-edge to break a fibre, giving a clean end-face, and fusion splicers use a hot electric arc
20 to join two fibres together at their ends. One process, fusion-tapering, is used to make a variety of fibre devices for performing some function on light passing along a fibre. In that process, a fibre is locally heated until it softens and then it is stretched so as to narrow the fibre locally
25 in the heated region. Light passing along the fibre is affected by the narrowness of the treated region. In a typical tapered single-mode fibre, the light spreads out from the core and occupies more of the surrounding cladding. If the fibre is sufficiently narrowed, the light spreads out
30 from the core completely and is then guided by the outer boundary of the entire fibre. The fibre is typically heated by immersion in a gas flame, proximity to an electrical heater or exposure to an intense laser beam.

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A tapered fibre that is cleaved at the narrowest point of the taper can act as a beam expander because the light wave has a greater cross-section at the cleave than it has in the untreated fibre. Such a beam expander can assist the
5 launching of light into the fibre and extraction of light from the fibre.

A fibre that is tapered so that light is locally guided at its outer boundary can act as a local optical sensor. In the tapered region, the light is sensitive to the medium
10 surrounding the fibre, whereas elsewhere it is insensitive because it is buried in the central core.

Two or more fibres that are tapered together in parallel contact can act as a fibre beam-splitter (or directional coupler), in which at least some of the light in
15 one fibre transfers across to the other fibre in the narrowed region.

In the last few years a non-standard type of optical fibre has been demonstrated, called the photonic-crystal fibre (PCF). Typically, this is made from a single solid,
20 and substantially transparent, material, such as fused silica glass, within which is embedded a periodic array of air holes, running parallel to the fibre axis and extending the full length of the fibre. A defect in the form of a single missing air hole within the regular array forms a
25 region of raised refractive index, which acts as a waveguiding fibre core within which light is guided, in a manner analogous to total-internal-reflection guiding in standard fibres. Another mechanism for guiding light is based on photonic-band-gap effects rather than total
30 internal reflection. Photonic-band-gap guidance can be obtained by suitable design of the array of air holes. Light of some propagation constants can be confined to the core and will propagate therein.

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Photonic-crystal fibre can be fabricated by stacking glass capillaries and canes on a macroscopic scale into the required shape, and then holding them in place while fusing them together and drawing them down into a fibre.

5 The PCF has a number of technologically significant properties; for example, it can support a single-mode over a very broad range of wavelengths, it can have a large mode area and thus carry high optical powers, and it can have a large normal dispersion at the telecommunications wavelength
10 of 1.55 microns. PCFs are typically not circularly symmetric, as a result of the stack-and-draw method typically used to make them.

Technological application of PCFs would be facilitated by handling and processing techniques parallel to those
15 described above for standard fibres. Unfortunately, some of those techniques are not appropriate for PCFs; for example, an attempt to fusion splice two PCFs together causes the air inside them to expand explosively, destroying the fibre ends being joined.

20 It is an object of the invention to provide PCF optical devices analogous to standard fibre devices. It is another object of the invention to provide a process for producing such devices.

According to the invention there is provided a photonic
25 crystal fibre including a plurality of longitudinal holes, in which at least some of the holes have a different cross-sectional area in a first region of the fibre, that region having been heat-treated after fabrication of the fibre, from their cross-sectional area in a second region of the
30 fibre, wherein the optical properties of the fibre in the heat-treated region are altered by virtue of the change in cross-sectional area of the holes in that region.

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The words "after fabrication" should be taken to mean any time after the fibre has been drawn.

The heat treatment processes that can be used are typically the same as those described above for fusion tapering of standard fibres. As with standard fibres, the heat treatment can be accompanied by stretching, to narrow the fibre down. In contrast to standard fibres, however, changes in optical properties can result without stretching the fibre at all; that is because heat treatment can allow some or all of the holes in the fibre to collapse partially or completely under the influence of surface tension. That can be achieved either with or without simultaneous stretching. Furthermore, if some of the holes are pressurised, they can be made to expand instead of collapse, and differential pressurisation of the holes can, in principle, be used to create any pattern of hole collapse and expansion. As with the tapering of standard fibres, for most applications, the transitions between untreated fibre and the middle of the heat treated region must be sufficiently gradual that an acceptably small amount of light is lost along the transition - the so-called criterion for adiabaticity.

It may be that at least some of the holes have expanded in the heat-treated region.

It may be that at least some, or all, of the holes have collapsed at least partially, or completely, in the heat-treated region.

The pattern of hole collapse and/or expansions may be not circularly symmetric. The birefringence of the fibre may be altered by the lack of circular symmetry.

The fibre may have been narrowed in the heat-treated region.

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The photonic crystal fibre may be included in an optical device.

The photonic crystal fibre may be included in a mode-field transformer, the transformer being arranged so that a guided mode propagating through the transformer will have its field distribution changed by propagation through the heat-treated region of the photonic crystal fibre. The shape and size of the field distribution of the guided mode in a PCF depends on the relative sizes of the air holes and their separations from each other. Thus a PCF that has been heat treated to change the sizes of the holes (or narrow down the entire fibre) can act as a mode field transformer.

The photonic crystal fibre may be included in a multi mode to single mode transformer or mode filter, in which the untreated regions of the fibre are multi mode and the heat-treated region is single mode for at least one wavelength of light. Light propagating through the treated region will be forced into a single mode and will remain substantially single mode when it passes into the untreated region, which is capable of supporting other modes; those other modes will, in an ideal fibre, remain unexcited.

The photonic crystal fibre may be included in a fibre input- or output- coupler, in which the photonic crystal fibre is cleaved in the heat-treated region. Such devices can be used to enhance the coupling of light into or out of the end of the fibre if the fibre is cleaved in the region of the heat treatment.

The fibre input- or output-coupler may be arranged so that, when a mode is propagating through the coupler, the mode pattern at the cleaved face will substantially match the mode shape of an external optical element. The external optical element may be a diode laser. Making the mode elliptical or rectangular will allow more efficient

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launching of light into the fibre from a diode laser source. Indeed, simply expanding the mode size will make easier launching of light from other sources into the fibre.

The fibre coupler may be included in a fibre splice, in which the fibre coupler is joined to one or more other fibres. The joining may, for example, be effected by fusion, by an adhesive or by abutment.

At least one of the one or more other fibres included in the fibre splice may be selected from the following: a cleaved photonic crystal fibre; a fibre coupler, as described above; a standard fibre; or a standard fibre that has been tapered by stretching during heat treatment and then cleaved. Controlled hole collapse provides a way of fusion splicing pairs of PCFs together. First the troublesome air holes are eliminated by their complete collapse in a portion of each fibre, as described above. It is not necessary to stretch the fibres. The fibres are cleaved at the portions where the holes have collapsed, and can then be fusion spliced, since there are no holes to explode and the mode fields will match. (If the fibres are not identical, one or both of them can be stretched so that their outer diameters match. Their mode fields will then be identical.) As an alternative to fusion splicing, two PCFs that have matched mode fields can be mechanically spliced using an adhesive in the conventional way.

A standard fibre tapered to the point where the light is guided by its outer boundary has a similar mode field to a PCF whose holes have collapsed completely and which has also been stretched to the same final diameter. The splice will then be low in loss.

A photonic crystal fibre according to the invention may be arranged so that interaction of light, propagating in the photonic crystal fibre, with the external environment is

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enhanced or suppressed in the heat-treated region. Such a photonic crystal fibre may be included in an optical device, such as, for example, a mode-field transformer. The interaction may facilitate measurement of a measurand of the fibre's external environment. The interaction may, for example, be with an external optical element. The optical element may comprise one or more other optical fibres. At least one of the one or more other optical fibres may be a photonic crystal fibre according to the invention or a standard fibre. The spreading out of the mode field caused by collapse of air holes will increase the intensity of the field at the outer boundary of the fibre. Light at the boundary is free to interact with the environment around the fibre. Interactions with the external environment can therefore be enhanced (or suppressed) by hole collapse (or expansion). If the light can interact with a particular property in the environment (for example, the external refractive index), the treated fibre will act as an environmental sensor. If a suitable optical element is placed next to the fibre, optical devices can be built based on the interaction with that element. In particular, the optical element can be at least one other fibre, which may be a PCF or a standard fibre and may have been fused to the first fibre during the heat treatment, in a similar process to the fabrication of fused directional couplers in standard fibres.

At least two fibres in the optical device may have been at least partly fused together by heat treatment.

Similarly, variation of the mode field can be used to control the interaction of the light in the core with any structure that has been introduced into the rest of the fibre. Examples of such structures are diffraction gratings, doped regions (which may be optically pumped to provide

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gain), or indeed additional guiding cores. Devices that can be based on such interactions include directional couplers, spectral filters, sensors and lasers or optical amplifiers. A photonic crystal fibre according to the invention may be arranged so that interaction of light, propagating in the photonic crystal fibre, with a structure (deliberately) introduced elsewhere in the fibre is enhanced or suppressed in the heat-treated region. Such a photonic crystal fibre may be included in an optical device. The introduced structure may, for example, be one of the following: at least one other core region in the photonic crystal fibre; a grating; or a region of doped material.

The optical device may be included in another optical device such as a directional coupler, a spectral filter, an optical sensor, a laser or an optical amplifier (which may in turn include a directional coupler).

Also according to the invention there is provided a method of producing a photonic crystal fibre, including the following steps: fabricating a photonic crystal fibre having a plurality of longitudinal holes; and heat-treating a region of the fibre so that at least some of the holes in that region have a different cross-sectional area from their cross-sectional area in regions of the fibre which have not been heat-treated, the optical properties of the fibre in the heat-treated region being altered by changing the cross-sectional area of holes in that region.

At least some of the holes may be pressurised during the heat treatment. All of the holes may be pressurised during the heat treatment.

The heat treatment may cause at least some, or all, of the air holes within the fibre to collapse completely in the treated region.

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It may be that the heat treatment is not applied in a circularly symmetric manner, so that a pattern of hole collapse and/or expansion that is not circularly symmetric results. The birefringence of the fibre may thereby be altered in the heat-treated region. The polarisation properties of a PCF depend on the structure in the vicinity of the core. Controlled variation of air hole sizes and overall fibre diameter can therefore be used to modify the birefringence of the fibre.

10 The fibre may be narrowed locally by stretching during the heat treatment.

The heat treatment may change the physical and/or chemical state of at least some of the material within the fibre.

15 An embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings, of which

Fig. 1 is a schematic cross-sectional view through a standard fibre.

20 Figs. 2a and 2b are schematic views showing heat treatment of a standard fibre.

Fig. 3 is a schematic cross-sectional view through a photonic crystal fibre of the prior art.

Fig. 4 is a schematic cross-sectional view through another photonic crystal fibre of the prior art.

Fig. 5 is a schematic view of an arrangement for carrying out heat-treatment of a fibre.

Fig. 6 is a schematic view showing the effect of heat treatment on a photonic crystal fibre.

30 Fig. 7 is a schematic view of a directional coupler or beam-splitter.

Fig. 8 is a schematic longitudinal section through a fibre splice.

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Fig. 9 is a schematic longitudinal cross-section through a multi-core fibre.

Fig. 10 is a schematic view of (a) an untreated photonic crystal fibre and (b) a photonic crystal fibre which has been heat-treated to produce birefringence.

Standard fibres, such as the one shown, for example, in Fig. 1, in their simplest form comprise essentially a cylindrical core 10 and concentric cylindrical cladding 20. Typically, both the core and the cladding will be made of the same material, usually silica, but each is doped with other materials in order to raise the refractive index of the core 10 and lower the refractive index of the cladding 20. Light, of appropriate wavelengths, is confined to the core 10, and guided therein, by total internal reflection at the core-cladding boundary 15.

It is known to heat-treat and stretch standard fibres in order to produce a stretched and narrowed region with optical properties different from those of the rest of the fibre (Figs. 2a and b). In Fig. 2a, the fibre is shown held by clamps 30 and is pulled in opposing directions parallel to its longitudinal axis 40. Heat 50 is applied to the fibre. The result of that treatment is shown in Fig 2b: a waist 60 is formed in the fibre. The cross-sectional area of the core 10 is greatly reduced and the cladding 20 is also significantly narrowed. There is a transitional region 70 between the waist 60 and the rest of the fibre 80.

A typical photonic crystal fibre, shown in Fig. 3, comprises a strand of transparent bulk material 90 (e.g. silica) with a lattice of holes 100, which run along its length. The holes are arranged at the vertices and centres of tessellating regular hexagons. The holes have a regular period, broken by the omission of one hole near the centre of the fibre. The region 110 of the fibre surrounding the

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site of the missing hole has the refractive index of the bulk material 90. The refractive index of the remainder of the fibre is attributable to the refractive index of both the bulk material 90 and the air in the holes 100. The refractive index of air is lower than that of, for example, silica and, consequently, the 'effective refractive index' of the material with the holes is lower than that of the region 110 surrounding the missing hole. The fibre can therefore confine light approximately to the region 110, in a manner analogous to waveguiding by total internal reflection in standard fibres. The region 110 is therefore referred to as the 'core' of the photonic crystal fibre.

In another form of photonic crystal fibre, photonic band gap guidance acts to confine light to the fibre 'core'. In the example of such a fibre shown in Fig. 4, there is a matrix of holes 120 in bulk material 90. The holes are arranged at the vertices (but not the centres, cf. Fig. 3) of regular hexagons. The regularity of the matrix is again broken by a defect, but it is, in the illustrated example, an additional hole 130 at the centre of one of the lattice hexagons, that hexagon being near the centre of the fibre. The area surrounding the additional hole 130 can again be referred to as the core of the fibre. Disregarding (for the moment) hole 130, the periodicity of holes in the fibre results in there being a band-gap in the propagation constants of light which can propagate in the fibre. The addition of hole 130 effectively creates a region that can support propagation constants different from those supported in the rest of the fibre. If some of the propagation constants supported in the region of hole 130 fall within the band-gap of propagation constants forbidden in the rest of the fibre then light having those propagation constants will be confined to the core and propagate therein. Note

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that because the hole 130 is a low-index defect (it results in air being where bulk material would otherwise be), total internal reflection effects are not responsible for that waveguiding.

5 A set-up suitable for use in heat-treatment of a photonic crystal fibre is illustrated in Fig. 5. The fibre 140 is clamped to stages 150, which are in a fixed position; there is no deliberate stretching of the fibre 140. A burner stage 160, having a burner arm 170 is arranged so
10 that a flame 180 heats a portion of fibre 140 between the stages 150. It should be noted that many other heating mechanisms are suitable for carrying out the invention, including, for example, heating with an electric heater or the beam of a carbon dioxide laser.

15 An example of the effects of heat treatment on a photonic crystal fibre are shown in Fig. 6. There is a heat-treated region 200, an untreated region 190 and a transition region 210. In the example shown, portions 230 of holes in the heat-treated region 200 can be seen to have
20 partially collapsed, when compared with portions 220 in the untreated region 190. The cross-sectional area of each of at least some of the holes therefore varies along the length of that hole. The overall diameter of the fibre will also reduce slightly, although the cross-sectional area of glass
25 240 in the untreated region 190 will be much the same as that of glass 250 in the treated region 200.

Fig. 7 shows the structure of an optical device that could be made using the photonic crystal fibre of the invention, namely a directional coupler or beam-splitter. A
30 region 280, 290 in each of two photonic crystal fibres 260, 270 is heat-treated according to the invention. Regions 280, 290 are fused together, for example simultaneously with the heat treatment or by further heat treatment. Light in

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the heat-treated regions 280, 290 extends into the cladding region of the fibre, because hole collapse has weakened or destroyed the refractive index difference between the cladding and the core. Light propagating in, for example,
5 fibre 260 will be coupled into fibre 270 where the fibres are fused together in regions 280, 290.

Splicing of a photonic crystal fibre 330 to a standard fibre 420 is shown in Fig. 8. Each fibre is heat-treated stretched and cleaved to produce tapered regions 340, 380.
10 In tapered region 340 of the photonic crystal 330, holes 300 are substantially eliminated. In tapered region 380 of standard fibre 420, both core 410 and cladding 400 taper whilst retaining their independent identities. The two fibres are joined by fusion splice 360.

15 Light mode 320 propagating in defect core region 310 spreads out to fill the full width of tapered region 340. Mode 350 in that region matches mode 370 in the tapered region 380 of standard fibre 420. Away from the tapered region 380, light is in the usual mode 390 of standard
20 fibre 420.

Fig. 9 shows a multi-core photonic crystal fibre 440. That Figure (like Figures 6, 8 and 10), shows a few holes only; there will be, of course, many holes in a real fibre. Holes 430 surround two cores 480, 490; those cores do not
25 interact optically in untreated regions of the fibre. In heat-treated region 450, holes 430 have partially collapsed. In that region, light propagating in either core 480, 490 can interact with light propagating in the other core. The heat-treated region 450 can then act as a localised
30 directional coupler.

The hexagonal symmetry of holes 500 about the core 510 of the fibre of Fig 10(a) can be broken by selective collapse of holes 520 by heat treatment to produce the two-

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fold rotational symmetry of Fig. 10(b). The birefringence of the fibre may be thus altered in the heat-treated region, as a fibre having such a symmetry will, in general, be birefringent

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Claims

1. A photonic crystal fibre including a plurality of longitudinal holes, in which at least some of the holes
5 have a different cross-sectional area in a first region of the fibre, that region having been heat-treated after fabrication of the fibre, from their cross-sectional area in a second region of the fibre, wherein the optical properties of the fibre in the heat-treated
10 region are altered by virtue of the change in cross-sectional area of holes in that region.
2. A photonic crystal fibre as claimed in claim 1, in which at least some of the holes have expanded in the heat treated region.
- 15 3. A photonic crystal fibre as claimed in claim 1 or claim 2, in which all of the holes have expanded in the heat treated region.
4. A photonic crystal fibre as claimed in any preceding claim, in which at least some of the holes have
20 partially collapsed in the heat-treated region.
5. A photonic crystal fibre as claimed in any preceding claim, in which at least some of the holes have collapsed completely in the heat-treated region.
6. A photonic crystal fibre as claimed in any preceding
25 claim, in which all of the holes have collapsed completely in the heat-treated region.
7. A photonic crystal fibre as claimed in any of claims 1 to 5, in which the pattern of hole collapse and/or expansion is not circularly symmetric.
- 30 8. A photonic crystal fibre as claimed in claim 7, in which the birefringence of the fibre is altered by the lack of circular symmetry.

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9. A photonic crystal fibre as claimed in any preceding claim, in which the fibre has been narrowed in the heat-treated region.
10. An optical device including a photonic crystal fibre as claimed in any preceding claim.
11. A mode-field transformer, including a photonic crystal fibre as claimed in any of claims 1 to 9, the transformer being arranged so that a guided mode propagating through the transformer will have its field distribution changed by propagation through the heat-treated region of the photonic crystal fibre.
12. A multi mode to single mode transformer or mode filter, including a photonic crystal fibre as claimed in any of claims 1 to 9, in which the untreated regions of the fibre are multi mode and the heat-treated region is single mode for at least one wavelength of light.
13. A fibre input- or output- coupler, including a photonic crystal fibre as claimed in any of claims 1 to 9, in which the photonic crystal fibre is cleaved in the heat-treated region.
14. A fibre input- or output-coupler according to claim 13, the coupler being arranged so that, when a mode is propagating through the coupler, the mode pattern at the cleaved face will substantially match the mode shape of an external optical element.
15. A fibre input- or output-coupler according to claim 14, in which the external optical element is a diode laser.
16. A fibre splice, including a fibre input- or output-coupler according to claim 13, in which the fibre coupler is joined to one or more other fibres.
17. A fibre splice according to claim 16, in which the fibre coupler is joined to one or more other fibres by fusion.

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18. A fibre splice according to claim 16, in which the fibre coupler is joined to one or more other fibres by an adhesive.
19. A fibre splice according to claim 16, in which the fibre coupler is joined to one or more other fibres by abutment.
20. A fibre splice according to any of claims 16 to 19, in which at least one of the one or more other fibres is a cleaved photonic crystal fibre.
21. A fibre splice according to claim 20, in which at least one of the one or more other fibres is a fibre coupler according to claim 13.
22. A fibre splice according to any of claims 16 to 21, in which one or more of the other fibres is a standard fibre.
23. A fibre splice according to claim 22, in which at least one of the one or more other fibres that is a standard fibre has been tapered by stretching during heat treatment and then cleaved.
24. A photonic crystal fibre as claimed in any of claims 1 to 9, which is arranged so that interaction of light, propagating in the photonic crystal fibre, with the external environment is enhanced or suppressed in the heat-treated region.
25. An optical device including a photonic crystal fibre according to claim 24.
26. An optical device according to claim 25, in which the optical device is a mode-field transformer.
27. An optical device according to claim 25 or claim 26, in which the interaction facilitates measurement of a measurand of the fibre's external environment.

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28. An optical device according to claim 25 or claim 26, in which the interaction is with an external optical element.
29. An optical device according to claim 28, in which the optical element comprises one or more other optical fibres.
30. An optical device according to claim 29, in which at least one of the one or more other optical fibres is a photonic crystal fibre according to claim 24.
31. An optical device according to claim 28 or 29, in which at least one of the at least one other optical fibres is a standard fibre.
32. An optical device according to any of claims 29 to 31, in which at least two fibres have been at least partly fused together by heat treatment.
33. A photonic crystal as claimed in any of claims 1 to 9, which is arranged so that interaction of light, propagating in the photonic crystal fibre, with a structure introduced elsewhere in the fibre is enhanced or suppressed in the heat-treated region.
34. An optical device including a photonic crystal fibre according to claim 33.
35. An optical device according to claim 34, in which the introduced structure is at least one other core region in the photonic crystal fibre.
36. An optical device according to claim 34, in which the introduced structure is a grating.
37. An optical device according to claim 34, in which the introduced structure is a region of doped material.
38. A directional coupler including an optical device as claimed in any of claims 33 to 37.
39. A spectral filter including an optical device as claimed in any of claims 33 to 37.

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40. An optical sensor including an optical device as claimed in any of claims 33 to 37.
41. A laser or optical amplifier including an optical device as claimed in any of claims 33 to 37.
- 5 42. A laser or optical amplifier including a directional coupler according to claim 38.
43. A method of producing a photonic crystal fibre, including the following steps:
- 10 (a) fabricating a photonic crystal fibre having a plurality of longitudinal holes;
- (b) heat-treating a region of the fibre so that at least some of the holes in that region have a different cross-sectional area from their cross-sectional area in regions of the fibre which have not been heat-treated, the
- 15 optical properties of the fibre in the heat-treated region being altered by changing the cross-sectional area of holes in that region.
44. A method according to claim 43, in which at least some
- 20 of the holes are pressurised during the heat treatment.
45. A method according to claim 44, in which all of the holes are pressurised during the heat treatment.
46. A method according to claim 43 or claim 44 in which the heat treatment causes at least some of the holes within
- 25 the fibre to collapse at least partially in the treated region.
47. A method according to claim 43 or claim 44, in which the heat treatment causes at least some of the holes within the fibre to collapse completely in the treated
- 30 region.
48. A method according to claim 47, in which the heat treatment causes all of the holes within the fibre to collapse completely in the treated region.

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49. A method according to any of claims 43 to 48, in which the heat treatment is applied in a non-circularly-symmetric manner, so that a pattern of hole collapse and/or expansion that is not circularly symmetric results.
50. A method according to claim 49, in which the birefringence of the fibre is altered in the heat-treated region.
51. A method according to any of claims 43 to 50, in which the fibre is narrowed locally by stretching during the heat treatment.
52. A method according to any of claims 43 to 51, in which the heat treatment changes the physical and/or chemical state of at least some of the material within the fibre.

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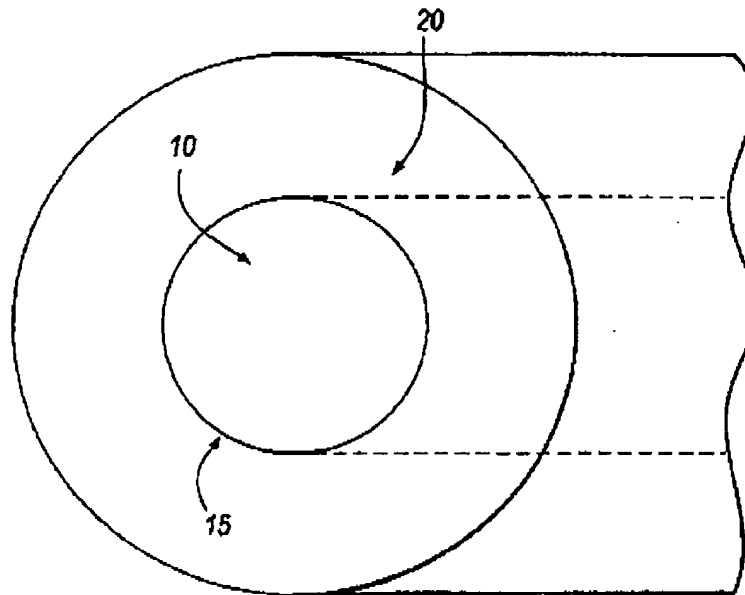


Fig. 1

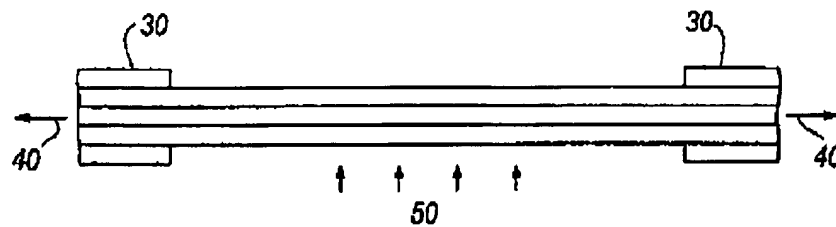


Fig. 2(a)

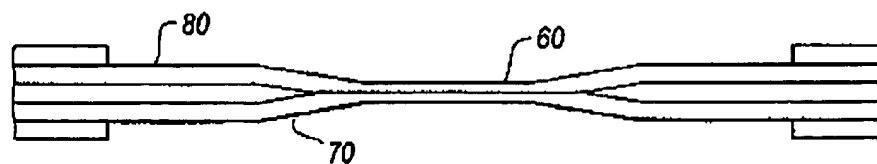


Fig. 2(b)

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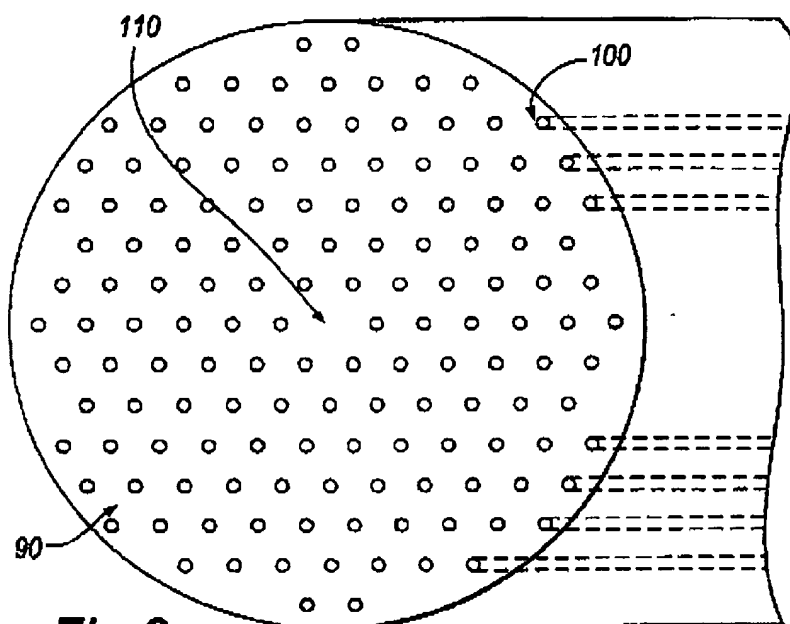


Fig. 3

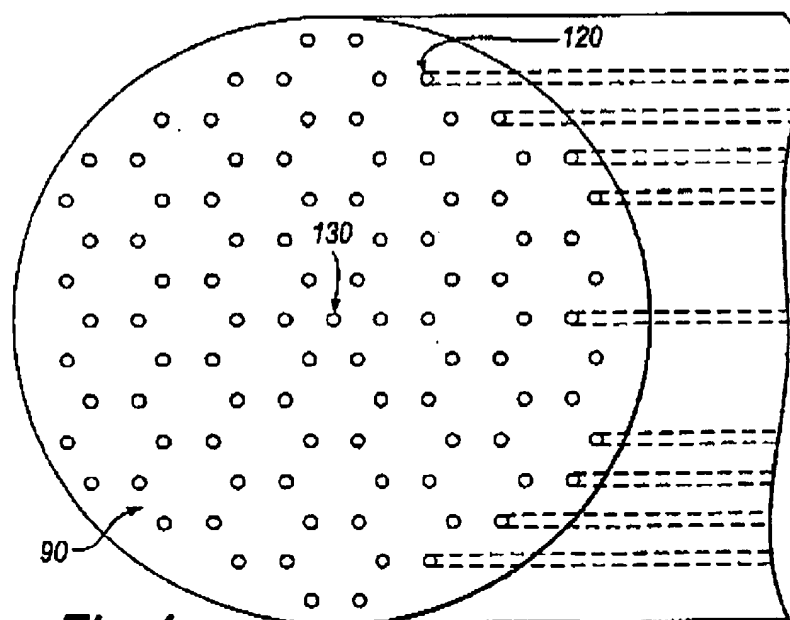
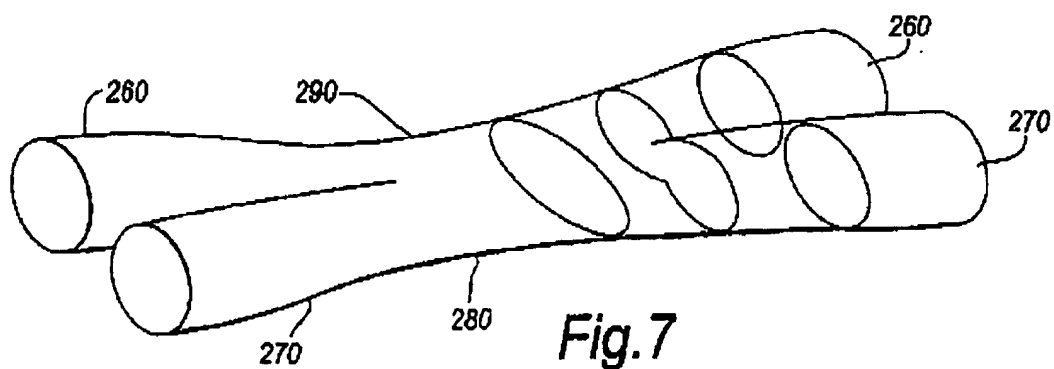
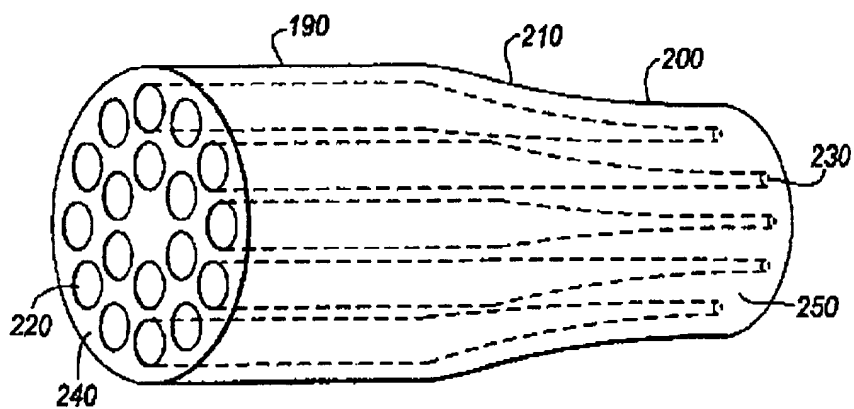
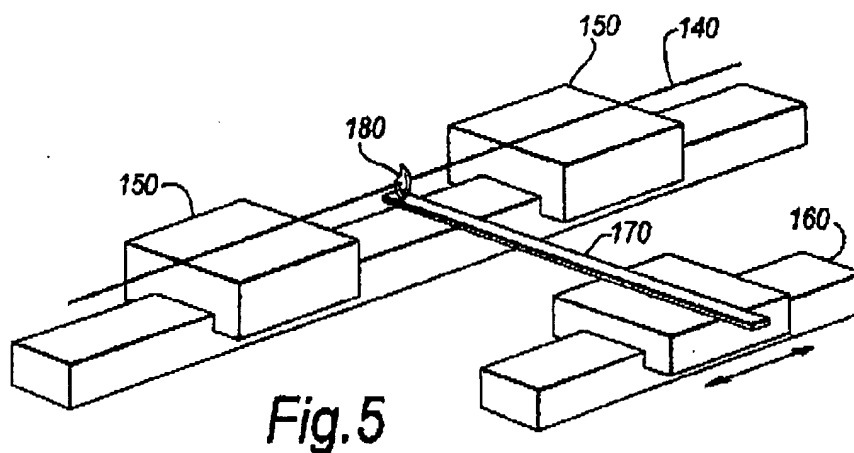


Fig. 4

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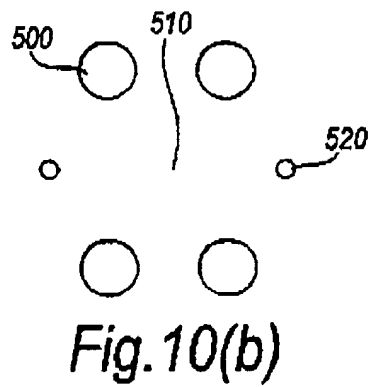
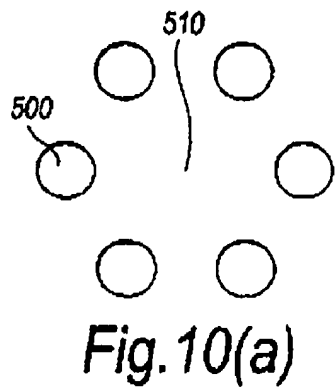
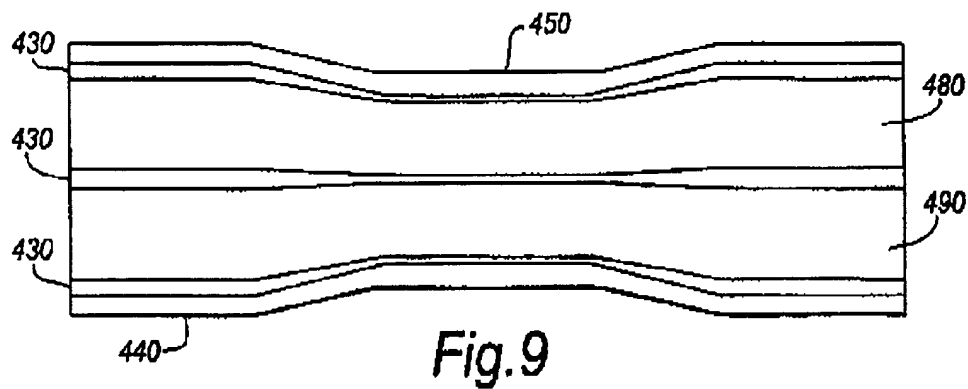
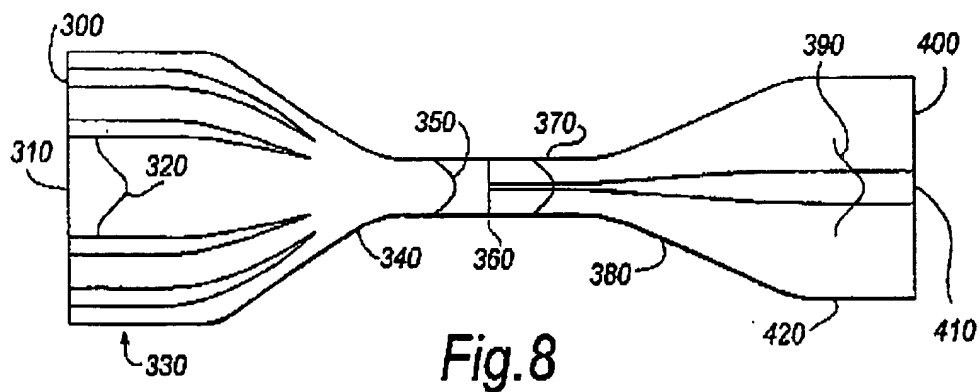
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INTERNATIONAL SEARCH REPORT

Int. Appl. No. PCT/GB 00/00599		
A. CLASSIFICATION OF SUBJECT MATTER IPC 7 602B6/16 C03B37/075 C03B37/027 G02B6/255 G02B6/28		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) IPC 7 G02B C03B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data bases consulted during the international search (name of data base and, where practical, search terms used)		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 802 236 A (DIGIOVANNI DAVID JOHN ET AL) 1 September 1998 (1998-09-01) column 1, line 26 - line 67 column 2 - column 4 column 5, line 1 - line 60 column 7, line 9 - line 67 column 8, line 1 - line 67 column 9, line 1 - line 48 figures 1-5 — -/-	1,7,33, 35-37, 41,43
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input checked="" type="checkbox"/> Patent family members are listed in annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "Z" document member of the same patent family		
Date of the actual completion of the international search 20 June 2000		Date of mailing of the international search report 28/06/2000
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 8280 HV Rijswijk Tel: (+31-70) 340-2040, Tx: 31 681 800 nl, Fax: (+31-70) 340-3016		Authorized officer Mathyssek, K

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	RUSSELL P ST J ET AL: "Silica/air photonic crystal fibres" JAPANESE JOURNAL OF APPLIED PHYSICS, SUPPLEMENTS, JA, JAPAN SOCIETY OF APPLIED PHYSICS, TOKYO, vol. 37, no. SUPPL. 37-01, 1998, pages 45-48-48, XP002111542 ISSN: 0021-4922 the whole document	1,43
A	BARKOU S E ET AL: "SILICA-AIR PHOTONIC CRYSTAL FIBER DESIGN THAT PERMITS WAVEGUIDING BY A TRUE PHOTONIC BANDGAP EFFECT" OPTICS LETTERS, US, OPTICAL SOCIETY OF AMERICA, WASHINGTON, vol. 24, no. 1, 1 January 1999 (1999-01-01), pages 46-48, XP000801368 ISSN: 0146-9592 the whole document	1,43
A	J.C.KNIGHT ET AL: "all-SILICA SINGLE-MODE OPTICAL FIBER WITH PHOTONIC CRYSTAL CLADDING" OPTICS LETTERS., vol. 21, no. 19, 1 October 1996 (1996-10-01), pages 1547-1549, XP000618354 OPTICAL SOCIETY OF AMERICA, WASHINGTON., US ISSN: 0146-9592 the whole document	1,43

Form PCT/ISA210 (continuation of second sheet) (July 1992)

page 2 of 2

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int. J. Appl. Application No

PCT/GB 00/00599

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5802236 A	01-09-1998	EP 0810453 A	03-12-1997
		JP 10095628 A	14-04-1998

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